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Solar-Powered Carbon Fixation for Food and Feed Production Using Microorganisms—A Comparative Techno-Economic Analysis

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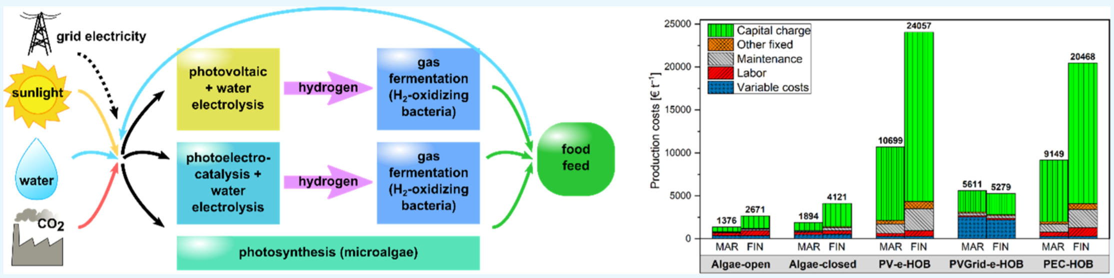

ABSTRACT: This study evaluates the techno-economic feasibility of five solar-powered concepts for the production of autotrophic microorganisms for food and feed production; the main focus is on three concepts based on hydrogen-oxidizing bacteria (HOB), which are further compared to two microalgae-related concepts. Two locations with markedly different solar conditions are considered (Finland and Morocco), in which Morocco was found to be the most economically competitive for the cultivation of microalgae in open ponds and closed systems (1.4 and 1.9 € kg^{-1}, respectively). Biomass production by combined water electrolysis and HOB cultivation results in higher costs for all three considered concepts. Among these, the lowest production cost of 5.3 € kg^{-1} is associated with grid-assisted electricity use in Finland, while the highest production cost of >9.1 € kg^{-1} is determined for concepts using solely photovoltaics and/or photoelectrochemical technology for on-site electricity production and solar-energy conversion to H_2 by water electrolysis. All assessed concepts are capital intensive. Furthermore, a sensitivity analysis suggests that the production costs of HOB biomass can be lowered down to 2.1 € kg^{-1} by optimization of the process parameters among which volumetric productivity, electricity strategy, and electricity costs have the highest cost-saving potentials. The study reveals that continuously available electricity and H_2 supply are essential for the development of a viable HOB concept due to the capital intensity of the needed technologies. In addition, volumetric productivity is the key parameter that needs to be optimized to increase the economic competitiveness of HOB production.

1. INTRODUCTION

Today, nutrient-rich feed and food can be produced from microbial biomass obtained by the cultivation of algae, bacteria, actinomycetes, yeasts, and molds and represent a resource-efficient alternative to traditional farming.[1,2] Dried cell preparations from these types of microorganisms contain high amounts of protein and are marketed as “microbial protein”, with an annual production capacity currently amounting to 124,000 t.[3] The nutritional use of microbial protein dates back to the 14th and 16th centuries, during which Aztech tribes inhabiting central Mexico used phototrophic cyanobacteria biomass known as Spirulina (*Arthrospira platensis* and *Arthrospira maxima*) as a food source. Renewed interest in Spirulina was triggered in 1967 by a nutritional analysis[4] and followed by efforts aiming at the development of novel types of edible inexpensive biomass. Consequently, new microbial protein products were introduced, including Pruteen in 1977 (methylotrophic bacterium *Methylophilus methylotrophus*), Quorn in 1985 (soil mold *Fusarium venenatum*), and Uniprotein in 1995 (methanotrophic bacterium *Methylococcus capsulatus*). While the production processes of these microbial proteins (i.e., excluding Spirulina) used organic compounds as microbial growth substrates (methanol, glucose, and natural gas, respectively),[5,6] more recent developments aim at more sustainable food production from CO_2 using photosynthetic microalgae[7] or hydrogen-oxidizing bacteria (HOB).[8]

The most efficient natural photosynthetic systems are microalgae. Their high conversion rate has inspired the research and development of biofuel production using microalgae, which was initiated in the 1970s and has since

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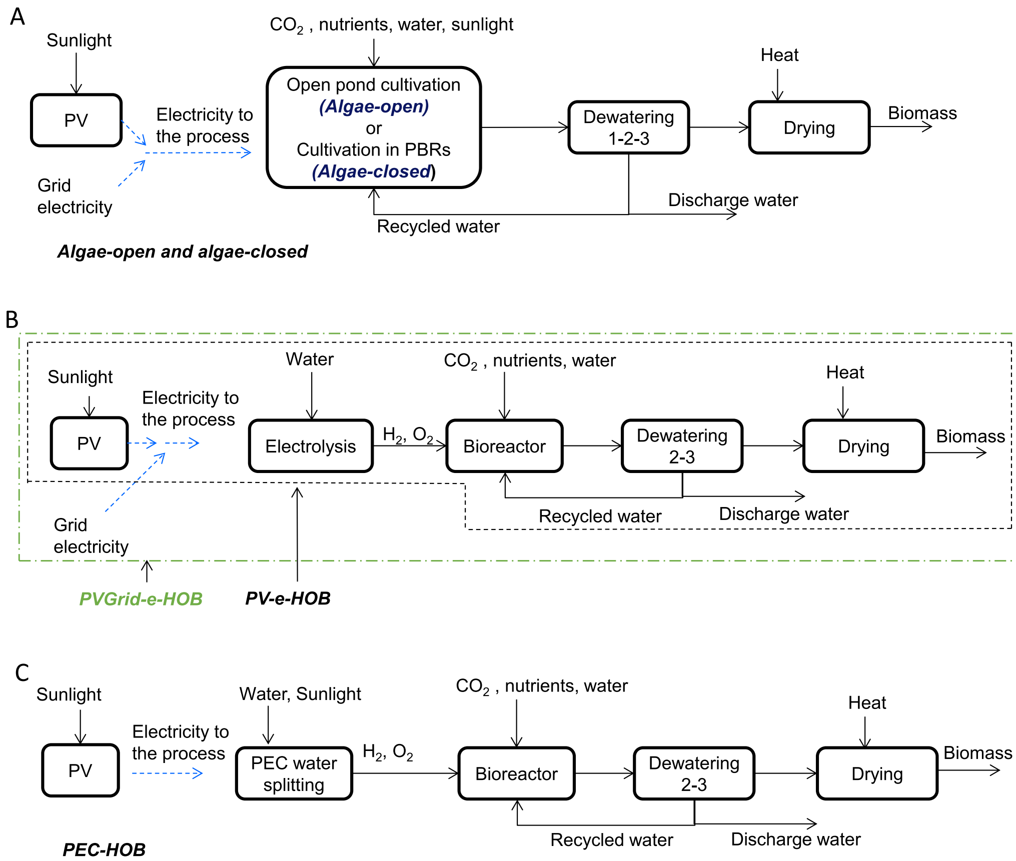

Figure 1. Block flow diagrams of concepts. (A) Algae-based biomass production concepts, algae-open and algae-closed; (B) Concepts utilizing PV and electrolysis combined with hydrogenotrophic fermentation, PV-e-HOB (dashed line), and PVGrid-e-HOB (dash dot line); (C) Concepts employing PEC water electrolysis and hydrogenotrophic fermentation, PEC-HOB.

provided exhaustive knowledge on microalgae cultivation.[9] The focus of the research had been on biofuels for a long time; however, in the past few years, it has expanded also onto feed, food, chemicals, and fertilizers as target products.[9,10] Commercial microalgae production started in 1960 in Taiwan and Japan, with the production of food supplements from *Chlorella* sp. and was extended during the past 5 decades thus far into low-volume, high-value products such as pigments, feed, and food additives, as well as nutraceuticals.[10,11] The advantage of microalgae lies in the high productivity cultivation process, the possibility to perform the production process on nonarable land, and their compatibility with cheap and abundant water sources such as wastewater, seawater, or brackish water. In addition, recent studies have found protein-rich microalgae-based animal feed to have benefits over conventional feed, including high contents of omega-3 fatty acids, antioxidants, and carotenoids.[12,13]

Unlike phototrophic organisms, HOB gain the chemical energy required for anabolic CO_2 reduction from the oxidation of H_2.[14] This growth substrate can be provided *in situ* from solar energy using a combination of photovoltaics (PV) and water electrolysis or photoelectrochemical (PEC) water splitting. PEC water splitting directly evolves H_2 and O_2 from water using solar energy. PEC water electrolysis is an emerging technology, with the largest reported PEC prototype module area of 64 cm^2[15] and another prototype holding the durability record of 17 d of continuous operation,[16] and it is rapidly maturing from prototype-based research to industry-oriented scale-up.[17] The combined use of water electrolysis and HOB cultivation may exceed the conversion efficiency of the microalgae cultivation process and allow biomass production in the dark. Another interesting aspect of the H_2 fermentative biomass production is that the yielded HOB biomass is rich in proteins, making up typically 30−75% of its dry weight.[18,19] Thereby, HOB biomass is comparable to established food protein products, such as soybean meal with 45% protein content;[8] moreover HOB biomass is an attractive protein source for food, feed, and fertilization applications. In addition to being the subject of academic research, HOB biomass production from CO_2 has recently become the focus of several commercialization efforts.[20]

Despite these benefits of microorganism biomass production, significant challenges for the commercialization of large-scale production still exist. In microalgae production, these include the high cost of cultivation and downstream process (DSP) operations, the potential for a negative energy balance after accounting for requirements in mixing, pumping, CO_2 transfer, harvesting and DSP itself, and further complications associated with culture stability.[21,22] For HOB production, challenges related to large-scale production include low CO_2 fixation efficiency, the safety concerns related to the use and storage of flammable gases on a production scale, as well as low substrate (H_2) solubility.[23,24] In addition, biomass production processes will need to comply with all current safety and health regulations. For example, concerns about cyanobacteria as a food source have been expressed due to the abundant capability of this bacterial phylum to produce harmful neurotoxins.[7,25]

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The present study examines and compares the techno-economic aspects of different biological systems for CO_2 fixation with solar energy. Furthermore, the techno-economic analysis aims at the identification of process parameters, which represent significant bottlenecks and should be optimized in order to improve the overall cost effectiveness of solar-powered biomass production. The evaluated concepts include large-scale production of biomass based on solar-powered CO_2 capture by HOB including PV-driven electrolysis and solar-powered CO_2 capture by HOB including H_2 production based on a PEC system. HOB production is further compared to phototrophic microalgae production.

2. RESULTS AND DISCUSSION

2.1. Assessed Concepts. This study evaluates five concepts with different solar-powered strategies for carbon capture for food and feed production. Two of these concepts employ photoautotrophic microalgae production, and three concepts utilize H_2 fermentation for biomass production. Of the latter, two utilize solar power as the main electric energy source, while one uses grid electricity, preferably from renewable sources, during periods of solar power unavailability. The target annual production of all concepts is 10,000 t as ash-free dry weight of biomass. Figure 1 presents the assessed concepts **algae-open** and **algae-closed**, **PV-e-HOB**, **PVGrid-e-HOB**, and **PEC-HOB** in three block flow diagrams. In the following chapters, the concepts and their parametrization are defined, with values adopted from a wide literature review.

The assessment is carried out for two different locations, selected at two different latitudes: Helsinki, Finland (60°N) and Agadir, Morocco (30°N). The main difference between the scenarios of the selected locations is solar irradiation, that is, the yearly average solar irradiation values in Morocco and Southern Finland are 2,200 and 950 kW h m^{-2} a^{-1}, respectively. Based on location-specific solar irradiation and standard sunlight condition on a clear day (1 kW m^{-2}), the PV capacity factors for the two locations are calculated as 10.8% for Helsinki and 25.1% for Agadir. The capital expenses differ between the locations due to different equipment size demand, but otherwise they are assumed to be location independent. The annual labor cost of one person is assumed to be 70,000 € in Finland and 35,000 € in Morocco. In addition, the unit cost of electricity varies with the location, and it is estimated as 70 € MW h^{-1} in Finland[26] and 100 € MW h^{-1} in Morocco.[27,28]

All concepts use CO_2 as the carbon source, which is purchased as a product from a power plant implementing carbon capture and utilization technology (i.e., amine scrubbing, oxy-combustion technology, etc. which may be expected to provide CO_2 at over 99% purity[29,30]). In the assessed design, pure CO_2 enters the plant via a pipeline and is stored in a pressurized storage sphere. According to the literature, the CO_2 capture cost varies between 32−47 € t^{-1},[29−31] and in the evaluation, the CO_2 cost 40 € t^{-1} is used.

The main nutrients, phosphorous and nitrogen, are assumed to be supplied in stoichiometric amounts to meet both microalgae and HOB biomass composition. The applied nutrients are diammonium phosphate (DAP) and ammonia, at a price of 567 and 695 € t^{-1}, respectively.[29] The nitrogen content of microalgae biomass may vary between 1 and 14% and the content of phosphorous between 0.05 and 3.3%.[32] This study assesses the production of protein-rich feed or food, and thus, the nitrogen content of microalgae is assumed to be rather high (10%). For HOB, the stoichiometric nitrogen content is retrieved from model organism *Cupriavidus necator*[33] shown in eq 1 and is 11%. Moreover, both microalgae and HOB are assumed to contain 0.8% of phosphorous in the ash-free dry product. The costs of other nutrients are considered small and therefore not evaluated in this conceptual study. In addition one may argue that microalgae can use nitrogen and phosphorous from wastewater,[34] but this may pose a health risk and the purchase of pure nutrients from commercial providers is considered here to ensure food safety.

Water from various sources including sea, brackish water, or, as mentioned earlier, even wastewater may be used for microalgae production, allowing the assumption that water is available free of charge in the microalgae-based concepts. The water quality requirements for electrolysis and for hydrogenotrophic fermentation are, however, higher than for microalgae cultivation, leading to a water cost evaluated to be 1 € m^{-3}. All concepts assume water recycling, where water discharge is set to 5% and compensated for by the addition of fresh water, which also considers possible evaporation losses and water evaporated from the product. The energy content of biomass for both microalgae and HOB is estimated to be 21.9 kJ g^{-1}.[35]

2.1.1. Concepts Algae-Open and Algae-Closed. Microalgae can be grown photoautotrophically, in which solar energy is utilized for CO_2 conversion into organic components of cell mass. The design and principle of algae cultivation systems may vary according to the specific needs of the selected microalgae strains, products, and environments. The two main design categories are open raceway ponds and photobioreactors (PBR), both of which are considered in this study, defined, respectively, as algae-open concept and algae-closed concept. The CO_2 demand is set as 1.83 kg per kg of ash-free dry biomass, based on the carbon need of biomass.[34]

The open-pond design and process parameters are chosen in accordance with the literature[29,36] and include a cultivation concentration of 0.5 g L^{-1}, a pond depth of 20 cm, a fraction of outgassed CO_2 being 25%, and specific electric energy consumption of 1.2 W m^{-3}. PBRs are closed and controlled environments, of which many different designs exist. Typically, the light penetration depth in PBRs is shorter than in open ponds, enabling a higher cultivation concentration. The risk of microbial contamination is also smaller in closed systems. The design in this study assumes the cultivation concentration to correspond to 2 g L^{-1}, the volume to surface ratio to be 0.05 m^3 m^{-2}, CO_2 outgassing to be 10%, and specific electric energy consumption to be 50 W m^{-3}.[21,29,37,38]

Because of low outside temperatures and dark winter times in Finland, microalgae cultivation is estimated to operate in Finland only from April to September. During this period, it is assumed that no external heating is needed and on average solar-energy input of 4.3 kW h m^{-2} d^{-1} is available, while this parameter decreases to 2.6 kW h m^{-2} d^{-1} when considered over the whole year.[39] Photosynthetic efficiency (PE) is estimated according to Weyer et al., (2010)[35] varying from 2.0 to 2.9% depending on the concept and scenario (see the Supporting Information for details). The average productivity obtained is 28.7 g m^{-2} d^{-1} for a PBR and 22.8 g m^{-2} d^{-1} for an open pond in Morocco (during a year-round cultivation period) and 18.5 and 14.2 g m^{-2} d^{-1}, respectively, in Finland (during a 6-month cultivation period). The costs for cooling of the PBR system are adopted from ref 37.

The evaporation and precipitation affect the water balance of the open system. The used model for estimations can be found from the Supporting Information. Monthly average balances are utilized resulting in estimated annual evaporation of 1306 mm for Morocco and a cultivation period evaporation of 306 mm for Finland. The evaluated size of the downstream equipment, including mechanical dewatering and drying, is derived from the peak season monthly production of microalgal biomass. Mechanical dewatering of biomass aims to a concentration as high as possible and thus minimize the need for an energy-intensive thermal drying. However, the contribution of mechanical dewatering of the biomass to the overall production costs is also significant and has been estimated in the literature to be between 20 and 30%.[40,41] This calls for the importance of technologies with low energy consumption values. The mechanical dewatering design selected for this study is based on a comprehensive techno-economic analysis of phototrophic microalgae production presented in ref 29. Settling is selected as the first dewatering step, by which the biomass concentration is increased to 1%. This step is followed by dewatering in a hollow-fiber membrane system (marked in Figure 1 as "Dewatering 2") and increases the biomass content further to 13%. The third dewatering step is centrifugation, by which the dry content is raised to 20%. Hollow-fiber membrane technology was selected primarily because of the favorably low energy consumption, that is, 0.04 kW h m^{-3}.[29] Centrifugation (Dewatering 3) is a well-understood technology that is widely used in industrial applications, which according to ref 29 consumes 1.35 kW h m^{-3} electrical energy. Harvested biomass is dried with a ring dryer up to 90% dry weight. The electricity consumption (90 kW h) and the fuel consumption (747 kW h) for evaporating 1 ton of water were estimated according to ref 42. Both microalgae concepts utilize grid-assisted PV electricity as an energy source. The PV capacity is sized such that the maximum instantaneous power output matches the necessary process power intake.

2.1.2. Concept PV-e-HOB. The possible maximum cell efficiency of PV depends, among other factors, on the type of used technology with the current benchmark for an experimental device exceeding 40% energy conversion efficiency.[43] However, commercially available PV equipment typically performs solar-energy conversion to electricity at around 20% efficiency.[44] Accordingly, this study assumes an efficiency of 20% and the concept PV-e-HOB assumes that PV-generated electricity is utilized as an exclusive electricity source.

H_2 is required for the HOB cultivation and can be produced via water electrolysis. Electrolysis at polymer electrolyte membranes (PEM) was selected as a means for H_2 production because it provides H_2 and O_2 in separate streams with a very high H_2 purity, and the CO_2–H_2–O_2 ratio is one of the key parameters that influence the energy efficiency of hydrogenotrophic fermentation. The International Energy Agency (IEA) determines the PEM electrolysis efficiency of 65–78%,[45] and an electrolysis efficiency of 70% was assumed in this study.

H_2 and O_2 from electrolysis, as well as CO_2, and other nutrients are distributed to the HOB fermentation process in which hydrogenotrophic microorganisms are able to produce biomass. HOB obtain the energy required for cell growth through the oxidation of gaseous H_2 coupled to the reduction of gaseous O_2. The overall stoichiometry of cell growth has been determined for the model organism *C. necator*[33] as

$$\begin{aligned} &21.36H_2 + 6.21O_2 + 4.09CO_2 + 0.76NH_3 \\ &\quad \rightarrow C_{4.09}H_{7.13}O_{1.89}N_{0.76} + 18.70H_2 \end{aligned} \tag{1}$$

Bacterial strain, growth conditions, and growth rate can affect the molar ratio of the consumption of gaseous substrates;[46] thus the energy efficiency of CO_2 fixation by HOB is dependent on the molar ratio of H_2 and CO_2. The efficiency of HOB fermentation is estimated as the yielded biomass per energy content of H_2, and an efficiency of 45.5% is used as a baseline value for this study obtained at a molar H_2:CO_2 ratio of 4[47] and a CO_2 usage of 1.85 kg per kg biomass.[33] These values result in a H_2 utilization ratio of 0.34 kg per kg biomass, which is somewhat higher but in line with the reported ratios of 0.28–0.30 kg H_2 per kg biomass.[48] For the continuous system,[48] growth rates of 0.03 and 0.09 h^{-1} with biomass concentrations of 3.1 and 1.2 g L^{-1}, respectively, were reported. For high concentration batch systems, an average productivity of 6.9 g L^{-1} d^{-1} is reported with a final biomass concentration of 41 g L^{-1}, while values for other batch trials were 22 g L^{-1} final biomass concentration and average productivity 3.1 g L^{-1} d^{-1}. The latter values are chosen as baseline values for this study.

HOB cultivation is performed in several parallel 1000 m^3 fermentation tanks. These require efficient agitation to maintain homogeneity and enable efficient heat transfer as well as to maintain efficient mass transfer between gaseous and aqueous phases.[49] The power consumption of bioreactors was estimated to be 1.2 kW m^{-3}[49] including both agitation and compression of gaseous reactants as well as the energy needed for the circulation of unused gases. The fermentation cooling need, caused by exothermic reactions, is estimated from the remainder between the energy content of H_2 and biomass. The electric energy demand in refrigeration is estimated to be 0.259 kW electricity per kW refrigeration.[50] The subsequent DSP steps—Dewatering 2, Dewatering 3 (see Figure 1), and drying, are similar to algae concepts. HOB concepts include one dewatering step less due to the higher biomass concentration in fermentation than in algae cultivation.

2.1.3. Concept PVGrid-e-HOB. The design of this concept is similar to the PV-e-HOB concept, with the exception of grid electricity usage as an additional electrical energy source, which enables continuous processing and thus decreases the design size of the equipment while still having the same biomass production capacity. Electrolysis and DSP are based on an annual production time of 8000 h. The PV capacity is designed in such a way that the instantaneous maximum power output equals the process electric power demand, and when the PV-driven electricity is not available, grid electricity is used. This combination introduces the need for a DC/AC inverter, which is assumed to perform the electrical power inversion at 95% efficiency.

2.1.4. Concept PEC-HOB. The design of the concept PEC-HOB includes a PEC system to produce H_2, which is fed into a bioreactor for HOB biomass production and processed similarly to the PV-e-HOB concept.

The accurate estimation of PEC efficiencies is complicated by the emerging nature of this technology and performed here by a comparison of relevant published reports. The practical limit of PEC efficiency is claimed to be 25%,[51] while Fountaine et al.[52] state a theoretical limit of 28%, which turns into a practical limit of 15% when considering the high-performance realistic case and 5% when taking into account the Earth-

Table 1. Mass and Energy Balance and Evaluated Areal Need for Assessed Biomass Production Plants with Annual Production Capacity of 10,000 t

	scenario[a]	algae-open	algae-closed	PV-e-HOB	PVGrid-e-HOB	PEC-HOB
land use, wet area (ha)	FIN	421	324			
	MAR	132	104			
land use, PV (ha)	FIN	1.1	5.2	161	20.2	64.4
	MAR	0.5	1.8	69.7	20.2	27.8
land use, PEC (ha)	FIN					117
	MAR					51
facility area (ha)	FIN	549	428	210	26	236
	MAR	172	138	91	26	102
bioreactor volume (m^3)	FIN	842,212	161,964	81,494	9677	81,494
	MAR	263,291	52,204	35,191	9677	35,191
total electric energy demand (MW h a^{-1})	FIN	8723	39,554	306,684	306,684	122,281
	MAR	7269	26,872	306,684	306,684	122,281
grid electricity (MW h a^{-1})	FIN	6651	30,160		270,266	
	MAR	5270	19,482		222,346	
PV electricity (MW h a^{-1})	FIN	2072	9394	306,684	36,419	122,281
	MAR	1999	7390	306,684	84,338	122,281
drying fuel demand (MW h a^{-1})	FIN, MAR	29,059	29,059	29,059	29,059	29,059
water demand (m^3 a^{-1})	FIN, MAR	2,757,634	288,000	60,227	60,227	60,227
CO_2 demand (t a^{-1})	FIN, MAR	24,400	20,333	18,500	18,500	18,500
DAP demand (t a^{-1})	FIN, MAR	341	341	341	341	341
ammonia demand (t a^{-1})	FIN, MAR	1128	1128	1244	1244	1244

[a]The scenarios Finland and Morocco are abbreviated FIN and MAR, respectively.

abundance of the necessary materials. The current record held by a laboratory prototype is 18.5% when the electrolyte has a neutral pH.[53] The main advantage of PEC-based designs over PV-e is the realization in a single device of the photon conversion and the electrochemical H_2 production.[54] Assessment studies typically state energy conversion efficiencies in the range of 10−12%,[55,56] and for this study, 12% was selected. The concept's dewatering process from fermentation to drying is similar to that in the PV-e-HOB concept.

2.2. Efficiencies of Solar-Energy Conversion into Biomass. All concepts discussed here aim at the production of biomass using CO_2 as the carbon source and solar light as the energy source. Their overall energy conversion efficiency was calculated as the product of the published efficiencies of the individual processes required for the conversion of CO_2 to biomass (see Section 2.1 for HOB-utilizing and Supporting Information Section S1 for microalgae-utilizing processes). Overall, the resulting baseline conversion efficiency from solar energy to biomass is lowest for microalgae, with values ranging between 2.0 and 2.9% depending on cultivation system and location;[35] see the Supporting Information for details. The highest conversion efficiency was determined for the concepts based on PV-e-HOB, with a value of 6.4%, while the concept PEC-HOB is predicted to perform at 5.5% efficiency. The solar conversion efficiency of PV-e-HOB is composed of the PV efficiency being 20%,[44] the electrolysis efficiency being 70%,[45] and the HOB fermentation efficiency being 45.5%.[33,47,48] The PEC-HOB efficiency is obtained from PEC efficiency (12%[55,56]) and the abovementioned HOB fermentation efficiency.

2.3. Comparison of Resource Requirements in Concepts and Scenarios. The five biomass production concepts discussed here show large differences in their main performance parameters based on an annual biomass production of 10,000 t of ash-free dry weight in Finland and Morocco (Table 1). The design size of reactors, electrolyzers, and DSP depends highly on the utility degree of process units, which can be seen when comparing the scenarios Finland and Morocco and also by comparing the grid-assisted concept PVGrid-e-HOB to the PV-e-HOB concept. The use of grid electricity in addition to PV electricity enables a high utility degree of biomass production and DSP and therefore the requirements for plant equipment size are lower, although still providing the same biomass production. However, the use of grid electricity reduces the share of solar radiation as the energy source, which can be illustrated by considering the concepts PV-e-HOB and PVGrid-e-HOB. In the latter, just 12% (Finland) or 28% (Morocco) of the consumed electricity is produced by PV, while the prior uses exclusively PV electricity.

In order to achieve identical production capacities in both scenarios, the decreasing solar irradiation at higher latitudes requires larger light harvesting modules. This is exemplified by (i) the wet area demands for microalgae cultivation being 421 ha for open systems (Finland) and 324 ha for closed systems (Finland) versus 132 ha for the open system (Morocco) and 104 ha for the closed system (Morocco), (ii) the PV-area demands (e.g., 161 ha (Finland) and 70 ha (Morocco) in PV-e-HOB concept), and the (iii) PEC area demands of 117 ha (Finland) and 51 ha (Morocco). The land occupied by algae-based concepts is, due to the lower solar-to-biomass conversion efficiency, over two times as large as the area needed for other concepts. In addition, for grid-assessed PV the land use is minimal.

As for the electrical energy consumption, the electrolysis concepts PV-e-HOB and PVGrid-e-HOB consume the largest amounts of electricity of approximately 307 GW h a^{-1}, with the water electrolysis accounting for 63% of the total power consumption. The share of HOB cultivation in power consumption is 36%, accounting for both mixing and cooling. The algae-open concepts have the lowest electricity consumption, with 7.3 and 8.7 GW h a^{-1} in the case of Morocco

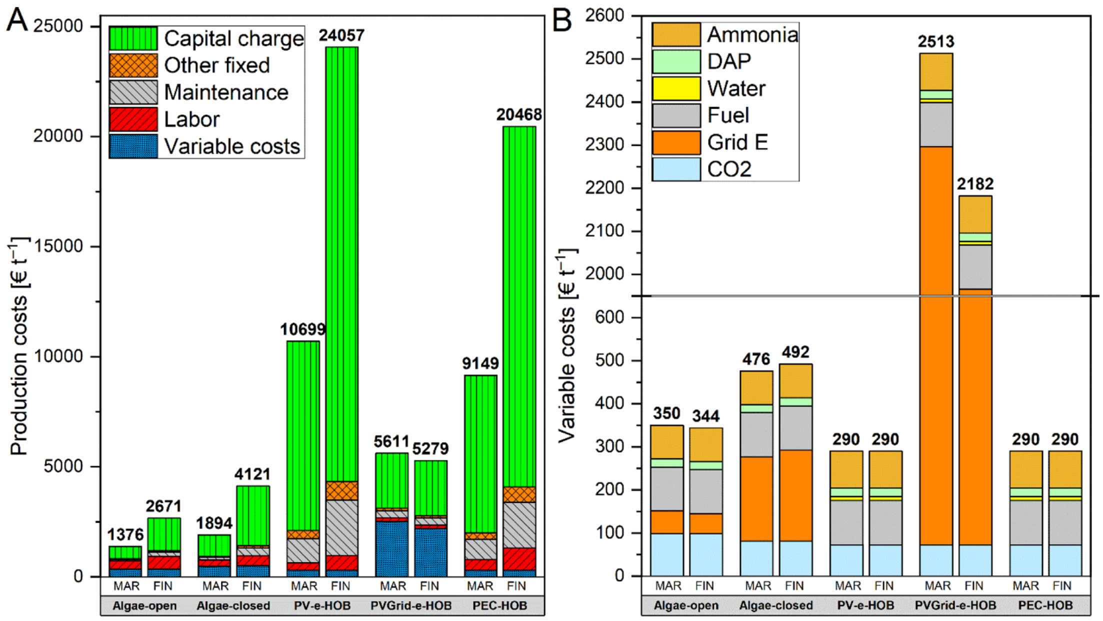

Figure 2. Total production cost of all concepts ("MAR" Morocco scenario, "FIN" Finland scenario) (A) and breakdown of variable production costs (B). The displayed variable cost parameters include CO_2, grid electricity (Grid E), fuel, fresh water, and nutrients ammonia as well as DAP.

and Finland, respectively. The electrical energy requirements are location-independent in the three concepts using H_2 fermentation, while in the two algae-based concepts, biomass production consumes more electric energy in Finland than in Morocco. This is emphasized in the algae-closed concept, where energy-intensive closed bioreactor cultivations are employed and where the electricity usage is one and a half times higher in Finland than in Morocco. Notably, both algal concepts are significantly more energy-efficient than the concepts employing HOB cultivation.

The requirement for ammonia nitrogen is slightly higher for HOB concepts than for algae-based concepts, while the other nutrients and drying fuel requirements are equal in all concepts. Even though the amounts of CO_2 fixed to biomass in all concepts are close to each other (1.83 kg per kg algae and 1.85 kg per kg HOB), the CO_2 demand in both algae concepts is higher due to outgassing from cultivations. Finally, significantly more water is consumed for the production of microalgae biomass than for the production of HOB biomass. This is most pronounced in the algae-open concept due to its low cultivation concentration and water evaporation. However, algae cultivation in general can use water from various sources (e.g., sea water, wastewater), making the water quality less critical than for HOB fermentation.

2.4. Economic Results. When the electricity demands of the production process are exclusively covered by the conversion of solar energy, the utility degree of the whole process follows the capacity factor of PV and PEC. This results in high capital expenses due to the fact that a major portion of the capacity remains unused during periods with absent solar irradiation. As evident from Figure 3, Finland, with its relatively low solar irradiation, is a challenging location for solar-powered biomass production due to an increased areal need and increased capital expenses when compared to production sites in proximity to the equator, such as Morocco.

As shown in Figure 2, differences in variable costs between the compared concepts mainly originate from the respective disparities and sources in the electricity demands. The use of solar energy results in a significant reduction in grid electricity costs, and in turn, variable costs are high in the concept PVGrid-e-HOB, where the electricity demand is covered to a large extent by using grid electricity.

All concepts, except PVGrid-e-HOB, are capital intensive, having shares of CAPEX in total production costs of 42−81% in Morocco and 48−82% in Finland (Figure 2). The total capital costs of the concept algae-open are the lowest, being 48 and 126 M€ for the scenarios Morocco and Finland, respectively, followed by algae-closed (82 and 231 M€), PVGrid-e-HOB (212 M€ for both), PEC-HOB (609 and 1395 M€), and PV-e-HOB (732 and 1680 M€). Details for capital expenses are given in the Supporting Information.

The baseline biomass costs (Figure 2) obtained in the algae-open and algae-closed concepts are 1376 and 1894 € t^{-1} (scenario Morocco). The biomass costs determined for concepts involving PV and water electrolysis (scenario Morocco) vary from 5611 to 10,699 € t^{-1}, and the costs from concept employing PEC water splitting is 9149 € t^{-1}. For the scenario Finland, the costs are roughly twice the costs of the scenario Morocco, with the aforementioned exception of PVGrid-e-HOB.

In general, HOB biomass production is more expensive than microalgae production. The main cost contributors for high capital expenses in PV-e-HOB and PEC-HOB concepts are the PV, electrolysis, PEC systems, as well the bioreactor itself. The low capacity factor increases capital costs significantly due to the low utility degree of equipment in the concepts PV-e-HOB and PEC-HOB.

2.5. Sensitivity Analysis. The comparative techno-economic study presented here demands a sensible approximation of many parameters and therefore displays intrinsic uncertainties and aspects that require to be assessed by a sensitivity analysis. Seventeen parameters were identified, and less favorable and more favorable values for each parameter were chosen based on published data. The background for this selection is described in the Supporting Information. The scenario Morocco was chosen over Finland for a compre-

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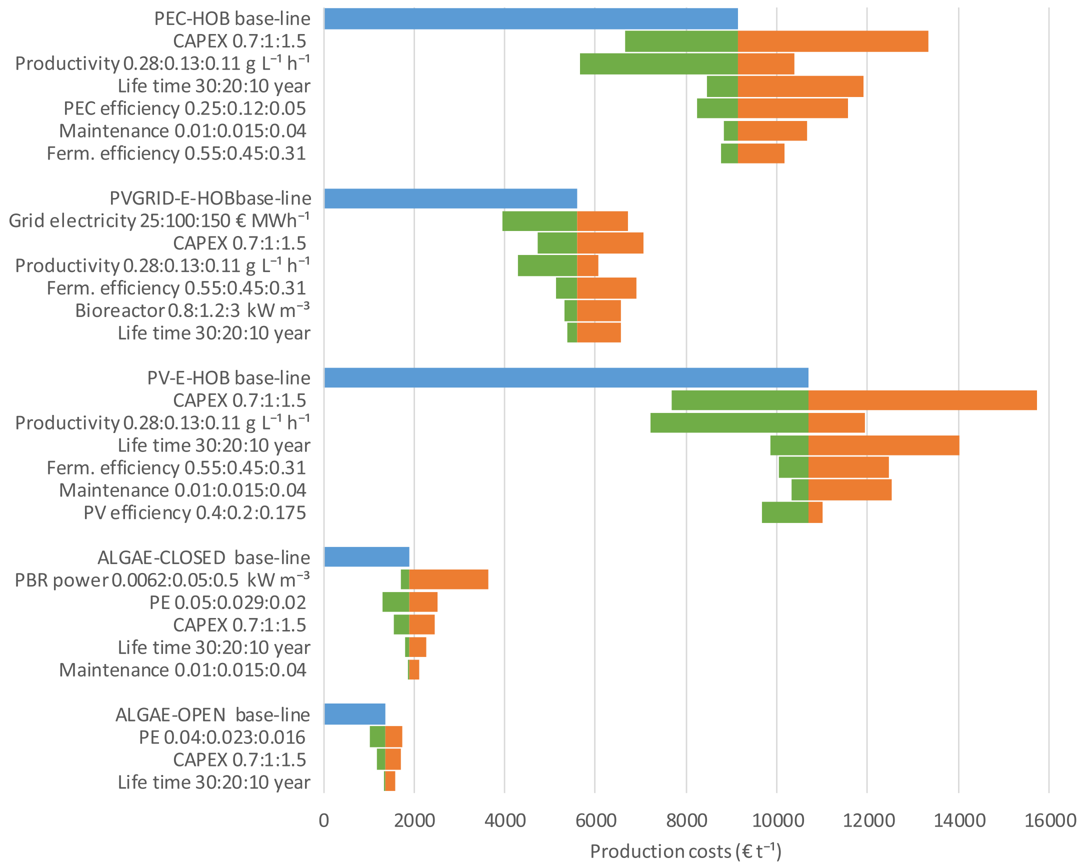

Figure 3. Sensitivity of production costs on key parameters in the scenario Morocco. Parameters exceeding 10% change in baseline cost are shown. Blue bars indicate baseline costs for each concept with variability of the costs by different parameters under favorable and less favorable conditions indicated by green and orange bars, respectively.

hensive sensitivity analysis because of its superior economic viability. Figure 3 summarizes the sensitivity analysis as multiple tornado diagrams, where the parameters with their less favorable and more favorable values are presented in the order of decreasing impact on the production costs.

As supposed, because of the capital intensity of the evaluated processes, the production costs of all concepts are sensitive to CAPEX, which is emphasized especially in the cases of PEC-HOB and PV-e-HOB that depend on solar energy as an exclusive electricity source resulting in a low utility degree of process equipment. In the concept PVGrid-e-HOB, the electricity cost has a major effect on HOB production costs. The presented analysis concept also implies that if in future continuously available electricity can be produced at low costs, it would be beneficial to HOB production. In general, the uncertainties related to HOB production are larger than the uncertainties related to microalgae production. Fermentation efficiency and productivity have a large impact on the process economy. The baseline productivity of the HOB system is 0.13 g L^{-1} h^{-1}, and a possible increase to the more favorable value of 0.28 g L^{-1} h^{-1}[148] implies a reduction in HOB biomass production costs by 23−38%. Likewise, PE is related to productivity in algae production and thereby one of the key factors affecting the production costs of algal biomass. The power consumption of PBR employed in the algae-closed concept may increase the biomass costs by 92% emphasizing the importance of power-efficient PBR technology for this process.

2.6. Consideration of Techno-Economic Characteristics of the Studied Concepts. This study provides a techno-economic evaluation of different strategies for the production of microbial biomass using solar power. It reveals the economic superiority of microalgal biomass production processes over those employing HOB cultivations. This is remarkable given the low energy efficiency of photosynthesis. Additionally, the study clearly identifies the importance of high solar irradiation for cost-effective production of microalgal and HOB biomass while using solar-based strategies. As opposed to microalgae, HOB do not directly use sunlight for biomass production and, thereby, the presented HOB-based technologies can be less affected by the low solar irradiation and thus appear as a particularly attractive option for microbial biomass production in countries with low solar irradiation. In such places, a continuous supply of non-solar renewable energy is required to support the biomass production process.

A comparison of the concepts PV-e-HOB and PVGrid-e-HOB in both scenarios reveals that the exclusive use of PV-derived electricity is not optimal because it results in a low utility degree of the plant and brings on high capital expenses due to an increase in plant size. PVGrid-e-HOB production concept significantly benefits from continuously available electricity source. However, while aiming at grid-assisted sustainable biomass production, the electricity grid of the location should have low greenhouse gas emission factors. Other options to be considered in further studies to enable high(er) utility degree for process and thus reduce the production costs include on-site storage of solar energy in the forms of either electricity or H_2 and exploitation of multiple renewable energy sources, such as wind power, for electricity production. Continuous production can be achieved by electricity storage, enabling the process itself to be run at a high utility degree regardless of the low capacity factor of PV. An alternative strategy could involve a combination of H_2 storage and the usage of grid electricity or stored electricity to operate HOB production at a high utility degree while H_2 could be produced using PV. In the PEC-HOB concept, H_2 storage would be also possible. Different mature technologies exist for H_2 storage, such as pressurized tanks and cryogenic tanks.[45] The IEA[45] has estimated the cost of H_2 storage in a pressurized tank to be 5400−9000 € MW h^{-1}. The Supporting Information provides the rough estimate of needed H_2 storage capacity to cover daily variation of production and estimates the needed size of a bioreactor and DSP to be half of the original while keeping the annual production capacity constant. The production costs in scenario Morocco will reduce to 8.0 and 6.2 € kg^{-1} for concepts PV-e-HOB and PEC-HOB, respectively. These are approximately 2.7−2.9 € kg^{-1} lower than the baseline costs showing evidence that concept optimization regarding the storage options for both H_2 and electricity would be relevant. In addition, the model was used to estimate the lowest possible price for HOB by optimizing the parametrization for PVGrid-e-HOB and applying the more favorable values from sensitivity analysis for four major cost contributors, that is, productivity, CAPEX, fermentation efficiency, and electricity cost. The potential future HOB biomass cost of 2.1 € kg^{-1} was obtained, which is dramatically lower than the baseline value of 5.6 € kg^{-1}.

The single most important process parameter affecting HOB production costs is volumetric productivity. The estimates of the volumetric productivity used in this study are adopted from a recently published report[48] and ranged between 0.05 and 0.29 g L^{-1} h^{-1}, which can be regarded as conservative estimates when compared to previously reported mixed-culture productivities of 0.27−0.38 g L^{-1} h^{-1}.[8,57] Improvement of productivity values, for example, by using mixed cultures would be beneficial for HOB production. Other means for the improvement of all analyzed concepts include the careful selection of a plant geographical location with high solar irradiation and taking into account the local infrastructure and the biorefinery approach with the coproduction of additional high-value applications, such as omega-3 fatty acids, special food supplements, or pharmaceuticals.

The recently reported algae biomass production costs vary from 0.4 to 12 € kg^{-1},[29,58,59] which are in line with the production costs of 1.3−4.1 € kg^{-1} that were estimated in the present study. The present study estimates the production costs of HOB biomass using exclusively solar-based strategies to be 9−24 € kg^{-1}, while the production costs for HOB biomass utilizing grid electricity in addition to solar energy are predicted to range between 5.3 and 5.6 € kg^{-1}. The previously reported production cost estimate of 2.5 € kg^{-1} for HOB biomass[60] is lower than the values obtained here. While the production system of the reference study is comparable to the PVGrid-e-HOB biomass concept of the present study and includes PEM for H_2 production, biomass cultivation, dewatering, and drying, the breakdown of electricity costs reveals that rather low cultivation costs were assumed. In addition, in the reference study,[60] the production of H_2 was evaluated with 50% lower electricity costs than the rest of the process, decreasing the production cost estimate significantly. Anyhow, the optimized cost for HOB obtained in this study (2.1 € kg^{-1}) compares well to the reference work.[60]

The present study estimates the production costs of algal and HOB biomass to be 1.3−4.1 and 5.3−24 € kg^{-1} (2.1 € kg^{-1} as optimized costs), respectively, and to exceed those of soybean being 0.27 € kg^{-1}.[3,61] Thus, the production of bulk products such as feed is currently economically out of reach. However, the microbial biomass production processes have certain advantages over traditional farming that may justify them under certain conditions. Farming of crops such as soybean occupies extensive areas of arable land and consumes large volumes of freshwater[3,61] and contains 30−40% of protein which is significantly lower than previously reported protein contents of microalgal and HOB biomass. In the context of novel alternative food sources, insect farming processes using food waste as feed stock have gained attention because they are an effective means to reduce food waste and provides a source of animal feed. With a protein content of 63% and a marketed value of 2−3 € kg^{-1},[62,63] black soldier fly larvae (*Hermetia illucens*) for animal feed are particularly noteworthy as its price compares positively to the evaluated production costs of algal biomass and approaches those of HOB. The present study reveals the potential of microalgae for the production of medium- and high-value commodities, that is, nutritional foods and cosmetics and in aquaculture, as larval feed or nutritional purposes. The potential of HOB biomass is more limited due to its higher production costs. However, the results show that improvements in HOB production technologies and the use of other renewable energy sources in addition to solar can significantly lower the production costs of HOB biomass to approach those of microalgal biomass and potentially enable the establishment of HOB biomass on the food market as a novel source of nutritional protein.

3. COMPUTATIONAL METHODS

Mass and energy balances for the assessed concepts are calculated using models constructed using the spreadsheet Microsoft Excel and based on the parameters described in the previous sections. Variable costs of production are based on balance calculations and on the unit costs of raw materials, chemicals, and energy. Depending on the concept, the following items are evaluated: CO_2, water, grid electricity, drying heat, and phosphorous- and nitrogen-based nutrients.

The capital cost estimates are derived from the literature as reference costs presented in detail in the Supporting Information. All costs are adjusted to correspond to the year 2018 €, utilizing the Chemical Engineering Plant Index for cost year corrections and currency conversion of 0.90 from \$ to €. The total capital investment is a sum of fixed capital costs, working capital, and land cost estimated according to the methodology described in ref 64. The land cost is evaluated separately, as the concepts occupy large land areas to have access to sufficient solar energy and assuming that the land cost equals the cost of barren land that is not possible to use, for example, for farm crop cultivation. The working capital is estimated as 5% of fixed capital investment. The relatively low number is justified by the few amounts of raw materials and chemicals needed.

The annual capital charge is calculated on the basis of 20 years of economic lifetime of the plant and with a 10% rate of return. Annual maintenance and other fixed costs are set at 2% of the total capital investment for all concepts. The reported estimates of labor amount in algae systems vary significantly

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being 1 person for every 2 ha[42,58] up to every 20 ha.[29] Here, 40 persons per 100 ha are assumed to be required for operation of the algae farm including DSP. The same labor amount is also used for the assessment of the PEC-HOB concept (see the Supporting Information). As a result, the production cost is calculated as the sum of all costs related to production. In other words, the production cost corresponds to a minimum selling price for biomass, as the break-even price to which biomass should be sold to obtain zero profit.

A sensitivity analysis is performed by first moving one input variable to a more favorable and a less favorable value at a time and keeping others at their baseline value and then returning the variable to its baseline value. This is repeated for each of the variables that are selected for the sensitivity analysis.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c04926.

> Additional details on solar to biomass efficiencies, precipitation and evaporation estimates, technology considerations and cost estimates, and parameter ranges for sensitivity analysis and state of the art PEC (PDF)

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Notes

The authors declare no competing financial interest.

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